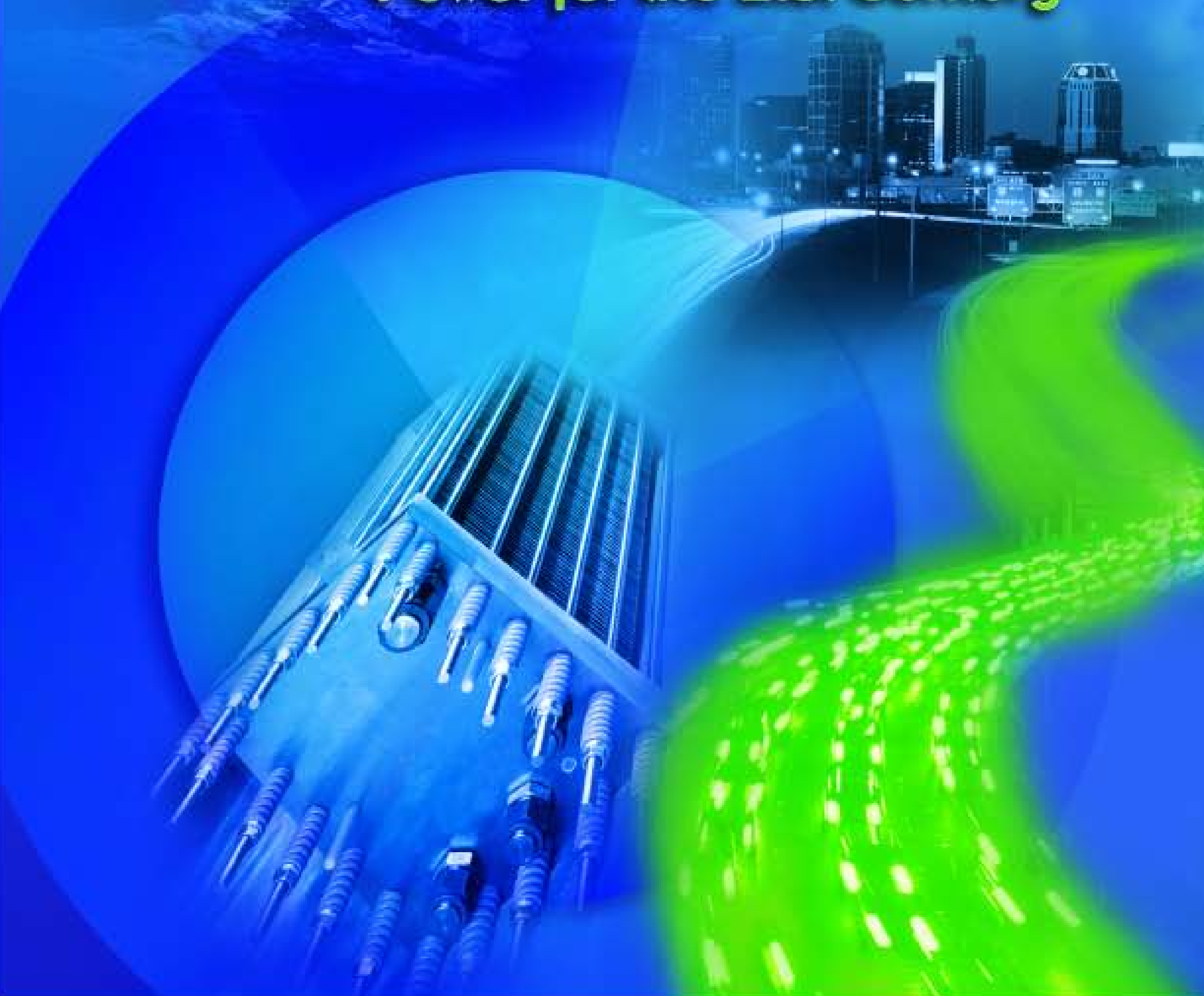
Fuel Cells

Power for the 21st Century



Hydrogen, Fuel Cells & Infrastructure Technologies Program

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable


Fuel Cells
Power for the 21st Century

AN INTRODUCTION

"Today there are more than 6 billion people on the planet. Only about 12% have powered vehicles. The math is sobering: What happens when even a fraction of the other 88% become mobilized? Clearly, the energy needs of the future cannot be met long-term with only fossil fuels... We need cleaner, renewable alternatives and we need them now."

— Robert C. Stempel, "Fueling the Future," Popular Mechanics

Scarcely a day goes by that we don't hear some mention of fuel cells or the new "hydrogen economy." Over the next several decades, we will begin to see an enormous shift away from the traditional use of fossil fuels we have today toward a much cleaner hydrogen future. In the months and years to come, we will be hearing more and more about the energy security and environmental benefits of using hydrogen and fuel cell technologies for our transportation, stationary power, and portable power needs. With breakthroughs in technology development, we are already heading toward a hydrogen economy.

But what does it all mean to us? What is a fuel cell? How does it work? Where will the hydrogen that powers the fuel cells come from? And can fuel cells really deliver on the promises that they will double the efficiency of our vehicles, safely warm and cool our homes and offices, power our cell phones and laptops, and significantly reduce air pollution?

In this book, we will try to answer some of the questions about fuel cell and hydrogen technologies — their history, their potential, and the challenges we must overcome to realize the vision of a new energy economy based on clean, renewable hydrogen.

This publication was prepared by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. For more information about how EERE is working with partners to accelerate the development and successful market introduction of fuel cell and hydrogen technologies, please visit us on the web at *http://www.eere.energy.gov/hydrogenandfuelcells.*

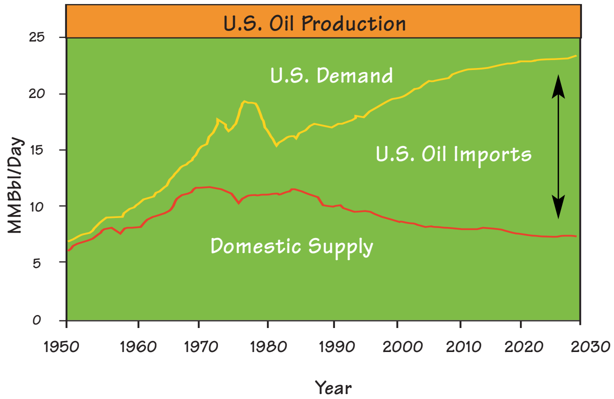
WHY WE NEED FUEL CELLS AND HYDROGEN

Since the major oil shortages of the 1970s, Americans have been dealing with the consequences of our nation's dependence on petroleum. Although petroleum products have taken us through the industrial and into the digital age, this dependence — along with issues such as air pollution and climate change — is leading us toward a hydrogen fuel cell economy.

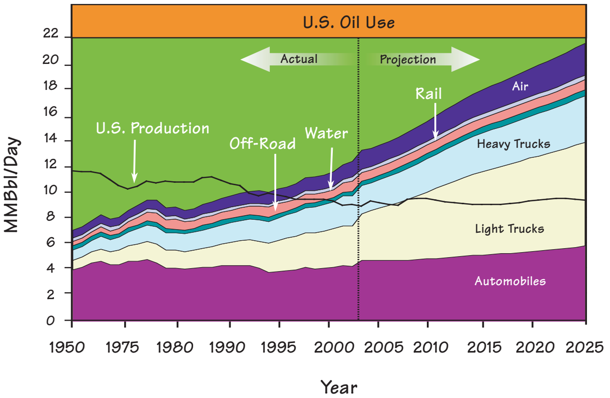
Energy Security

Like most of the world, the United States is dependent on petroleum for transportation, heating, and manufacturing. Our automobiles, trains, and planes are fueled almost exclusively by gasoline and diesel fuel. Our power plants run on oil, natural gas, and coal. We use electricity generated by burning fossil fuels to light our cities and communicate with one another. Building materials and plastics — even clothing and appliances — are made by using petrochemicals.

Like other countries, the United States cannot produce enough oil to meet demand, so we import it from oil-rich countries, making us economically dependent. Although our country consumes 26% of the world's oil (about 20 million barrels per day [mmBbl/day]), we produce just 9% of the global supply and account for only 3% of the world's petroleum reserves; about 65% of those resources lie beneath the Persian Gulf states.[1] When foreign oil producers decide to raise the price of oil, the United States — like the rest of the world — has little choice but to pay the higher price.



Domestic oil production falls well short of U.S. demand.[2]



There has been a dramatic increase in transportation-related petroleum use over the last three decades; projections show that this trend will continue.[2]

As a nation, we have nearly doubled our daily oil imports, from 5.8 million barrels per day in 1975 to 10.9 million barrels per day in 2001. The percentage of our daily oil demand being supplied by foreign imports has grown by almost 50% — from 36% to 55% since 1975,[3] and imports are expected to increase to 62% by 2020.[4] DOE estimates that by 2015, the demand for energy will grow by 54% worldwide and by 129% in developing Asia.

Unless the United States takes dramatic steps to reduce fuel consumption, this growing dependence on imported oil will put us at serious risk. A world crisis that interrupts shipment of oil for any prolonged period could disrupt our nation's economy. There would be no way for us to transport products, drive to work, fly to meetings, and heat and light homes and businesses. We must find new ways, then, to reduce our growing dependence on imported oil.

Air Pollution and the Environment

When car and truck engines burn gasoline, they also produce

- Carbon monoxide (CO), a poisonous gas, and
- Nitrogen oxides (NO_X) and unburned hydrocarbons, the main sources of urban ozone.

Emission rates of gasoline vehicles have fallen by 70–90% over the past three decades, thanks to such technologies as catalytic converters, more stringent air pollution control regulations, and improvements in refining techniques. These are important advances, but even as vehicles get cleaner, the pollutants they emit still cause problems — including dangerous levels of ozone in big cities — because we drive more miles, and we drive in larger vehicles, than ever before.

"The most urgent, long-term security requirement for the United States is to reduce our dependence on imported oil by developing clean, safe, renewable energy systems and energy conservation programs."

— Rear Admiral Eugene Carroll, U.S. Navy, Retired, Deputy Director, Center for Defense Information

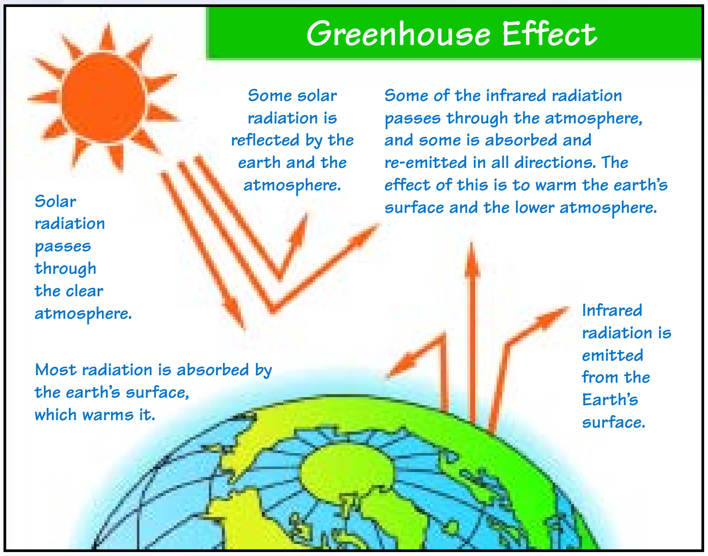
[1] *Union of Concerned Scientists, Dangerous Addictions, Ending America's Oil Dependence, 2002.*
[2] *Source for graphics: Transportation Energy Data Book: Edition 23, ORNL-6970, October 2003, and DOE's Energy Information Administration, Annual Energy Outlook, January 2003. Available at http://www-cta.ornl.gov/data*
[3] *Oak Ridge National Laboratory, Transportation Energy Survey Data Book 1.1, May 2002.*
[4] *From DOE's Energy Information Administration, Annual Energy Outlook, 2002.*

"Successful application of fuel cell technologies in automobiles will improve energy security and provide significant environmental benefits. A 10% market penetration could reduce U.S. oil imports by 130 million barrels per year. Fuel cell vehicles will reduce urban air pollution and mitigate climate change. They will be 70–90% cleaner than conventional gasoline powered vehicles on a fuel cycle basis, and will produce 70% fewer carbon dioxide emissions."

— Federal Energy Research and Development for the Challenges of the Twenty-First Century, The President's Committee of Advisors on Science and Technology

It has been estimated that 60% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment.[5] People exposed to air pollutants at sufficient concentrations and over long enough periods may face an increased risk of developing cancer or suffering other serious health effects, including damage to the immune system, as well as neurological deterioration, reduced fertility, learning disabilities, and asthma.

In many U.S. communities, ozone-related smog becomes a problem during the summer months. In the Earth's lower atmosphere, near ground level, ozone is formed when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources react chemically in the presence of sunlight. Ground-level ozone concentrations may lead to serious health effects.



Since the beginning of the industrial revolution, atmospheric concentrations of carbon dioxide have increased by nearly 30%, methane concentrations have more than doubled, and nitrous oxide concentrations have risen by about 15%.These increases have enhanced the heat-trapping capability of the earth's atmosphere. Fossil fuels burned to run cars and trucks, heat homes and businesses, and power factories are responsible for about 98% of U.S. carbon dioxide emissions, 24% of methane emissions, and 18% of nitrous oxide emissions. (Adapted from the U.S. Environmental Protection Agency's Climate Change Site [http://yosemite.epa.gov/oar/globalwarming.nsf/content/climate.html])

Climate Change

Every time a gallon of gas is burned in your car, about 5 pounds of carbon are released into the atmosphere. If you consider the entire fuel cycle, including production, transportation, and storage, the number jumps to 6.5 pounds.[6] If the emissions were solid carbon, it would be like throwing a 6.5-pound bag of charcoal briquets out the window of your car for every gallon of gas burned. But the carbon comes out as an invisible gas — carbon dioxide.

The carbon dioxide released from vehicles cannot be easily reduced by using add-on control devices, such as a catalytic converter. And, unlike CO, NO_x, and unburned hydrocarbons, greenhouse gas emissions — contributing to climate change — are not regulated by the U.S. Environmental Protection Agency. Many experts correlate the increase in greenhouse gases in the atmosphere with increases in the planet's temperature.

5 http://www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/2.0_program_benefits.pdf

6 Argonne National Laboratory, Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model.

A SOLUTION: FUEL CELLS AND HYDROGEN

The environmental advantages of a hydrogen economy are so promising that the push toward hydrogen is very strong. In the coming decades, the United States will need new energy supplies and a better energy infrastructure to meet growing demands for electric power and transportation fuel. Hydrogen and fuel cells seem to offer the best path toward meeting these goals. Here's why:

- Fuel cells, when fueled by pure hydrogen, generate almost no EPA-regulated air pollutants (like sulfur and NO_x, CO, and unburned hydrocarbons). DOE has estimated that if only 10% of the cars and light-duty trucks on the road were powered by fuel cells, more than a million tons of air pollutants would be avoided each year.

- Hydrogen poses fewer of the environmental dangers, like oil spills, associated with petroleum.

- Use of fuel cells could reduce U.S. dependence on foreign oil. If just 10% of cars used fuel cells, the United States could cut oil imports by well over 100 million barrels per year. A significant reduction in oil use would mean that the United States would be much less dependent on foreign oil.

- With 10% of vehicles powered by fuel cells, carbon dioxide emissions would be reduced by 60 million tons a year. If the hydrogen that powers fuel cells were made by using electricity from truly renewable sources (e.g., solar or wind power), producing hydrogen would add almost no greenhouse gases to the environment.

- Fuel cells can provide pollution-free energy for both transportation and electric utilities.

- Fuel cells can be made quiet, reliable, easy to maintain, and safe. Because fuel cell systems have few moving parts, they could potentially be more reliable and require less maintenance than internal combustion engines, the most common engines in today's market.

- Fuel cells are modular; they can be installed on sites as energy demand warrants without investing in large, centralized power plants and new high-voltage lines.

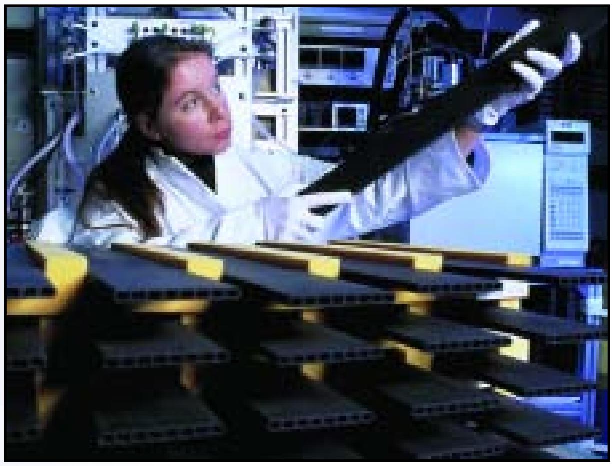
"We, at GM, believe that hydrogen represents the future of the motor vehicle. We regard the hydrogen fuel cell as the best strategy, over the long term, for reducing the world's dependence on petroleum and eliminating CO_2 emissions."

— Rick Wagoner
Chairman and Chief Executive Officer
General Motors Corporation

Many people incorrectly assume that all electric vehicles (EVs) are powered by batteries. Actually, an EV is a vehicle with an electric drivetrain powered by either an onboard battery or fuel cell. Batteries and fuel cells are similar in that they both convert chemical energy into electricity very efficiently, and they both have fewer moving parts than an internal combustion engine. However, the reactants in a battery are stored internally and, when used up, the battery must be either recharged or replaced; this is not the case with fuel cells. With a fuel-cell-powered EV, the fuel is stored externally in the vehicle's fuel tank and air is obtained from the atmosphere. As long as the vehicle's tank contains fuel, the fuel cell will produce energy in the form of electricity and heat. Fuel cells could eliminate the long recharging times and sudden power loss sometimes associated with batteries.

WHAT ARE FUEL CELLS?

Unlike an internal combustion engine, fuel cells rely on electrochemical reactions rather than combustion of fuel to generate power. And, unlike a battery, a fuel cell does not run down or require recharging; it operates as long as fuel is supplied. Because a fuel cell converts the chemical energy of the fuel directly into electricity, it's cleaner and more efficient than any carbon-fueled engine.



Photograph courtesy of Siemens-Westinghouse.

Because of their high efficiency, fuel cells are among the most promising technologies for the next generation of electrical power.

When hydrogen is used as the fuel in a fuel cell, water and heat are the only by-products. Because hydrogen is the most abundant element in the universe, it can be produced from a variety of sources. Hydrogen can be produced from electrolysis of water by using renewable solar, wind, hydro, or geothermal energy or by means of coal-burning or nuclear power plants. Hydrogen also can be extracted from resources that contain hydrocarbons, including gasoline, natural gas, biomass, landfill gas, methanol, ethanol, methane, and coal-based gas. In large-scale production of hydrogen from hydrocarbons, carbon would be captured and sequestered so that it is not released into the atmosphere.

HISTORY

Although many people are just hearing about fuel cells, the technology has actually been around for over 150 years. They were generally considered a curiosity in the 1800s, but since World War II, fuel cells have become the subject of intense research and development. The technology found its first real application when the National Aeronautics and Space Administration (NASA) began using alkaline fuel cells as one of the onboard systems to provide power during the Gemini and Apollo space programs. Below is a brief overview of a few of the earlier fuel cell researchers and their contributions.

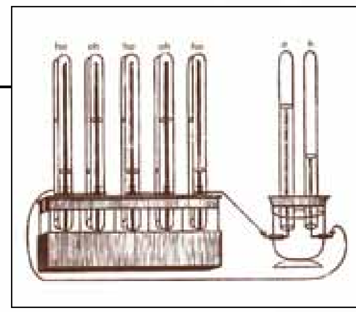
William Robert Grove, an English lawyer turned scientist, won recognition for his development of an improved wet-cell battery in 1839. The "Grove cell," as it came to be called, used a platinum electrode immersed in nitric acid and a zinc electrode in zinc sulfate to generate a current of about 12 amperes at about 1.8 volts.

Grove discovered that by taking two platinum (Pt) electrodes and immersing one end of each in a container of sulfuric acid with the other ends placed separately in sealed containers of oxygen and hydrogen, he could make a constant current flow between the electrodes. The sealed containers held water as well as the gases, and he noted that the water level rose in both tubes as the current flowed. Grove realized that by combining several sets of these electrodes in a series, he might "effect the decomposition of water by means of its composition." He soon accomplished this feat with the device he named a "gas battery" — the first fuel cell.

Francis Thomas Bacon began researching alkaline electrolyte fuel cells in the late 1930s.

In 1939, he built a cell that used nickel gauze electrodes and operated under pressures as high as 3,000 psi. During World War II, Bacon worked on developing a fuel cell that could be used in Royal Navy submarines, and in 1958, he demonstrated an alkaline cell using a stack of 10-inch-diameter electrodes. Though expensive, Bacon's fuel cells proved reliable enough to attract the attention of a company that licensed his work for the Apollo spacecraft fuel cells.

Since the space program in the 1960s, the federal government has supported research and development focused on fuel cell technology; hundreds of companies around the world are working to make fuel cell technology pay off. Just as in the commercialization of the electric light bulb nearly one hundred years ago, today's companies are being driven by technical, economic, and social forces — such as the emergence of new technologies and the need for clean energy supplies at affordable prices.



1839	Sir William Grove invents first fuel cell (H_2SO_4 + platinum electrodes, H_2 and O_2)
1896	William Jacques develops fuel cell for household use
1900	Walther Nernst first uses zirconia as a solid electrolyte
1921	Emil Baur constructs the first molten carbonate fuel cell
1930s	Francis Bacon researches alkaline electrolyte fuel cells; Emil Baur and his colleague H. Preis experiment with solid oxide electrolytes
1950s	Research into solid oxide technology begins to accelerate in the United States and the Netherlands; Allis-Chalmers Manufacturing Company demonstrates a 20-horsepower fuel-cell-powered tractor
1962	General Electric develops first polymer electrolyte membrane (PEM) fuel cell; Nafion® first introduced; more stable PEM fuel cell constructed
1965	Space applications: alkaline fuel cell used in Apollo missions; PEM fuel cell used in Gemini missions
1973	Oil crisis creates new impetus for fuel cell funding; phosphoric acid and molten carbonate fuel cells developed initially
1992	First commercial power plant begins operation (200-kW PC25 phosphoric acid fuel cell)
2002	Vehicle and stationary fuel cell systems enter several test markets

Graphic courtesy of the Proceedings of the Royal Society and photograph courtesy of the U.S. Army.

POTENTIAL APPLICATIONS

"Fuel cells, with their roots in the space program, have the potential to truly revolutionize power generation."

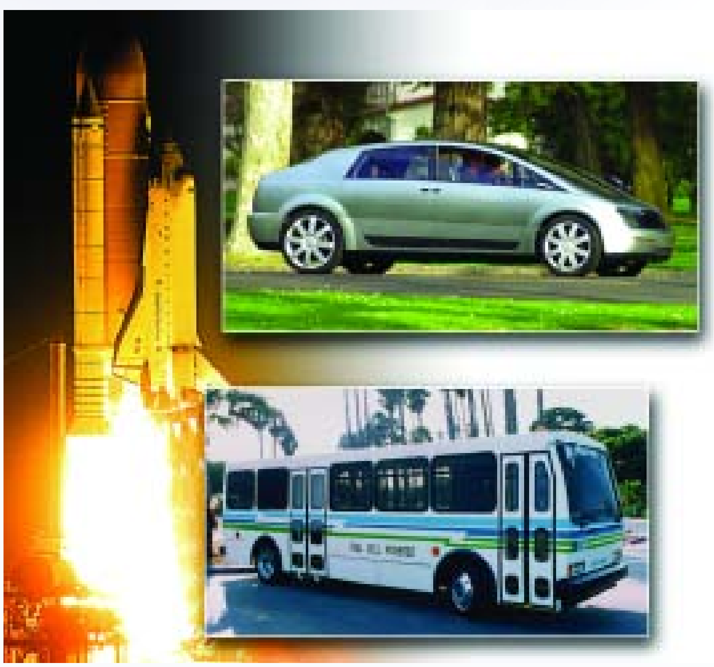
Dr. Mark C. Williams, U.S. Department of Energy, NETL, and Dan Rastler, Electric Power Research Institute, "Fuel Cells, Realizing the Potential"

The fuel cell is unique in terms of the variety of its potential applications: it can provide power for systems as large as a utility power station and as small as a smoke detector.

Over the next decade, products will emerge that are both more efficient and more environmentally benign than their predecessors. The century-long reign of internal combustion engines will almost certainly be challenged by fuel-cell-powered cars, buses, and light trucks that are quiet and clean and use energy far more efficiently than today's vehicles.

Naval forces in several countries are looking into fuel cells to run submarines and provide auxiliary power on oceangoing vessels; the U.S. Army is building a backpack-sized fuel cell generator that can power a soldier's electronics gear, from night-vision goggles to infrared heat detectors. Even construction equipment and farm vehicles can be converted to run on hydrogen.

Photographs courtesy of Georgetown University, NASA, and General Motors.



Transportation applications include cars, trucks, buses, boats, airplanes, aerospace vehicles, and scooters.

Typical Power Requirements

Computer = 50 W
House = 2–10 kW
Small Car = 50 kW
Small Commercial Building = 250 kW

Within a few years, fuel cells may power small electrical devices that now use batteries; your laptop computer may eventually run on a fuel cell that can run for days, rather than hours.

In general, the potential applications of fuel cells can be divided into three categories: transportation, stationary uses, and portable uses. Each is discussed below.

Charts on the following web page also provide information about the different fuel cell vehicles and products available: *http://www.fuelcells.org/info/charts.html.*

Transportation

Fuel-cell-powered cars, light trucks, and sport utility vehicles (SUVs) will likely start to replace those with gasoline and diesel engines within the next two decades. All of the world's major carmakers have intensive fuel cell research programs, and most have working prototypes. Manufacturers are focusing on light-duty vehicles because they offer the greatest payback in terms of energy independence.

Fuel-cell-powered buses are being demonstrated in cities around the world. The bus was one of the first applications of the fuel cell, because initial fuel cells needed to be quite large to produce enough power to drive a vehicle; buses were the only vehicles that had the space to spare. In the first fuel cell bus, about one-third of the vehicle was filled with fuel cells and fuel cell equipment. The technology has improved to the point that a bus can run on a much smaller cell.

Another transportation-related application for fuel cells is as auxiliary power units (APUs) for tractor-trailer trucks. APUs are used to provide heat and power for truck cabs during off-road rest periods; if they are used instead of engine idling, they could help save millions of gallons of diesel fuel each year, reduce carbon dioxide and criteria emissions by several million tons each year, and increase vehicle operating efficiency.

Stationary Uses

Stationary applications for fuel cells include buildings and power plants. Today, only about one-third of the electricity produced by power plants reaches the user because of losses from transmission and distribution power lines. In fact, fossil and nuclear plants in the United States vent more heat into the atmosphere than all the homes and commercial buildings in the country use in one year! Using fuel cells for utility applications can improve energy efficiency by as much as 60%, and yet reduce environmental emissions.

As fuel cell power generation technology is perfected, huge central power plants will likely be replaced by modular fuel cell units located where the power will be used. Fuel cell generators, which are relatively quiet and generate only trace pollution, can be placed close to consumers without violating local noise and pollution ordinances. Large fuel cells will be able to generate electricity more efficiently than today's power plants. The fuel cell technologies being developed for these power plants will generate electricity directly from hydrogen in the fuel cell, but they will also use the heat and water produced in the cell to power steam turbines and generate even more electricity.

Fuel cells have already been installed in hotels, hospitals, offices, and other buildings to provide electricity and meet space and water heating needs.

A phosphoric acid fuel cell system provides supplemental power to New York City's Condé Nast Building at 4 Times Square. The building has 48 stories and approximately 1.6 million square feet. For more on the building's innovative environmental design, visit www.eere.energy.gov/buildings/info/documents/pdfs/29940.pdf.

Image courtesy of Kiss+Cathcart.

"If New York City had a power blackout, the Central Park police station would continue to glow like a beacon inside a dark forest. That's because the station gets all its electricity from a 200-kilowatt fuel cell right outside the building, not from electrical utility lines. The fuel cell, which is about the size of a small delivery truck, produces a reassuring low hum."

— Catherine Greenman, "How It Works: Fuel Cells Provide Clean, Reliable (and Pricey) Electricity," New York Times, May 10, 2001

Portable Uses

Portable power applications include consumer electronics and auxiliary power — from cell phones, vacuum cleaners, and laptops to electric power units for heating the cabs of long-haul trucks and recreational vehicles. Fuel cells make sense for these applications because they last longer than a battery and can be quickly refueled with a liquid or gaseous fuel. Portable systems can be as small as approximately 20 watts (W) and as large as 30 kilowatts (kW). The hydrogen/air or methanol/air polymer electrolyte membrane (PEM) — also called proton exchange membrane — fuel cell technology is the system of choice for low-power applications. Both polymer electrolyte membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) operating on hydrogen from onboard storage or onboard processing of fossil fuels are candidates for high-power systems. The suitability of PEMFCs and SOFCs for these applications is discussed in more detail on pages 15–16.

Photographs courtesy of Motorola, Ballard Power Systems, and Fujitsu Limited.

Lithium-ion batteries are currently used for cell phones and laptops; to be successful in these applications, PEM fuel cell systems must exceed the performance and energy density of these batteries at about the same cost or have other attributes that make them a reasonable choice.

Photograph courtesy of Matt Striveson.

The chemical reaction in a single fuel cell produces less than 1.16 volts of electricity, so many separate fuel cells must be combined into fuel cell "stacks."

One of the most promising PEM fuel cell applications is as a replacement power source in the small electronic battery market. The success of these portable power fuel cell systems in the marketplace could pave the way for commercialization of stationary and transportation/propulsion fuel cell systems by demonstrating the safety of fuel cells, providing a manufacturing base, and facilitating the development of codes and standards.

HOW DO PEM FUEL CELLS WORK?

The Fuel Cell Stack

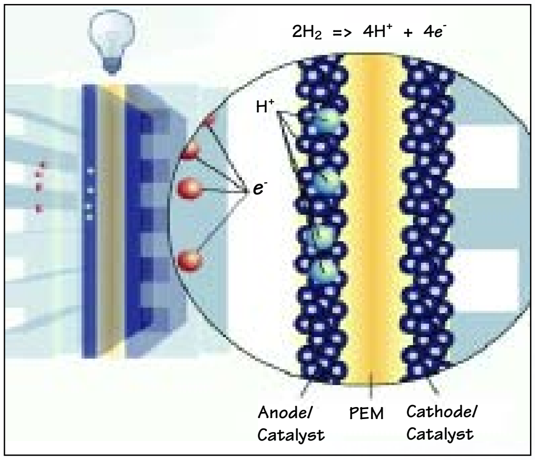
A fuel cell power system has many components, but its heart is the fuel cell stack. This stack is actually made of many thin, flat cells layered together like slices in a loaf of bread. Most individual fuel cells designed for use in vehicles produce less than 1.16 volts of electricity — far from enough to power a vehicle. Therefore, multiple cells must be assembled into a fuel cell stack. (The term "fuel cell" is often used to refer to the entire stack, but, strictly speaking, it refers only to the individual cells.) Each cell produces electricity, and the output of all the cells is combined to power the vehicle or for other applications. The potential power generated by a fuel cell stack depends on the number and size of the individual fuel cells that comprise the stack.

The PEM Fuel Cell

There are several kinds of fuel cells, but PEM fuel cells are the type typically used in vehicles, so we will address PEM fuel cells here. Each fuel cell contains several layers of different materials, as shown in the illustration to the right.

A single PEM fuel cell consists of two electrodes and two layers of catalyst, separated by a polymer electrolyte membrane. On one side of the cell, hydrogen gas flows through channels to one of the electrodes (the anode). On the other side of the cell, oxygen gas, typically from the outside air, flows through channels to the other electrode (the cathode).

The hydrogen on the anode side moves through the cell and encounters the first of two catalyst layers. The catalyst causes the hydrogen molecules to oxidize into hydrogen protons, giving up their electrons to the neighboring anode. While the protons migrate through the PEM to the second catalyst layer, on the other side of the cell, the stream of negatively charged electrons follows the path of least resistance — an external circuit — to the cathode. It is this flow of electrons through the external circuit that creates electricity.



A fuel cell consists of an anode, a cathode, and an electrolyte membrane.

Water and Heat

When the electrons return from doing work — lighting your house, charging a battery, or powering your car's motor, for example — they react with oxygen and the hydrogen protons at the cathode to form water. Most of the water is collected and reused within the system, but a small amount is released in the exhaust as water vapor. Heat is generated from this union (an exothermic reaction), as well as from the frictional resistance of ion transfer through the membrane. This thermal energy can be used outside the fuel cell.

What Else is in a Fuel Cell?

Other layers of materials are designed to help draw fuel and air into the cell and to conduct electrical current through the cell. Each fuel cell component and its role is described in more detail on the following pages.

The Anode and Cathode

The anode, the negative side of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. Channels etched into the anode disperse the hydrogen gas equally over the surface of the catalyst.

The cathode, the positive side of the fuel cell, also contains channels that distribute the oxygen to the surface of the catalyst. It conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.

The PEM — a specially treated material that looks something like ordinary kitchen plastic wrap — conducts only protons and blocks the electrons. The PEM is the key to the fuel cell technology: it must permit only protons to pass between the anode and cathode. Other substances passing through the electrolyte would disrupt the chemical reaction.

Oxidation-Reduction

All electrochemical reactions consist of two separate reactions: an oxidation half-reaction at the anode and a reduction half-reaction at the cathode (see box below). Oxidation involves a loss of electrons by one molecule, and reduction involves a gain of electrons by another. Both oxidation and reduction occur simultaneously and in equivalent amounts during any reaction involving either process.

Normally, the two half-reactions would occur very slowly at the low operating temperature of the PEM fuel cell. To speed up the reaction of oxygen and hydrogen, each electrode is coated on one side with a catalyst layer. The catalyst is usually made of platinum (Pt) powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the Pt can be exposed to the hydrogen or oxygen. The Pt-coated side of the catalyst faces the PEM.

Platinum-group metals are critical to catalyzing reactions in the fuel cell, but they are very expensive. DOE's goal is to reduce the use of Pt in fuel cells or eliminate it altogether to decrease the cost of fuel cells to consumers.

Membrane Electrode Assembly

The electrodes (anode and cathode), catalyst, and PEM and gas diffusion layer (GDL) together form the membrane electrode assembly. The thickness of the membrane in a membrane electrode assembly can vary with the type of membrane. The thickness of the catalyst layers depends upon how much Pt is used in each electrode. For catalyst layers containing about 0.15 milligrams (mg) Pt/cm^2, the thickness of the catalyst layer is close to 10 micrometers (μm) — less than half the thickness of a sheet of paper. This membrane electrode assembly, with a total thickness of about 200 μm (or 0.2 mm), can generate more than half an ampere of current for every square centimeter of assembly area at a voltage of 0.7 volts, but only when encased in well-engineered components: GDLs, flow fields, and current collectors.

Oxidation half reaction $2H_2 \longrightarrow 4H^+ + 4e^-$

Reduction half reaction $O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$

Cell reaction $2H_2 + O_2 \longrightarrow 2H_2O$

Gas Diffusion Layers, Flow Fields, and Current Collectors

The GDLs, flow fields, and current collectors are designed to maximize the current from a membrane electrode assembly. The GDLs — one next to the anode, the other next to the cathode — are usually made of a porous carbon paper or carbon cloth, about as thick as 4–12 sheets of paper. The layers have to be made of a material (like carbon) that can conduct the electrons that leave the anode and enter the cathode. The porous nature of the material ensures effective diffusion (flow of gas molecules from a region of high concentration to a region of low concentration) of each reactant gas to the catalyst on the membrane electrode assembly. The gas spreads out as it diffuses so that when it penetrates the GDL, it will be in contact with the entire surface area of the catalyzed membrane.

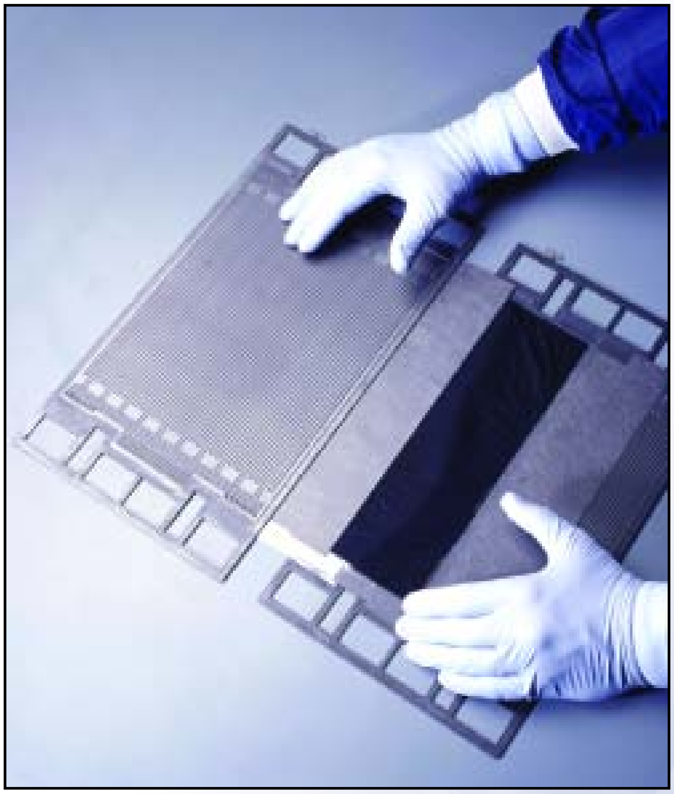
The GDLs also help in managing water in the fuel cell. The correct diffusion material allows the right amount of water vapor to reach the membrane electrode assembly and keep the membrane humidified. The GDLs are often coated with Teflon™ to ensure that at least some, and preferably most, of the pores in the carbon cloth (or carbon paper) do not become clogged with water.

Pressed against the outer surface of each GDL is a piece of hardware called a bipolar plate that typically serves as both flow field and current collector. In a single fuel cell, these two plates are the last of the components making up the cell.

The first task served by each plate is to provide a gas "flow field." Channels are etched into the side of the plate next to the GDL. The channels carry the reactant gas from where it enters the fuel cell to where it exits. The pattern of the flow field in the plate (as well as the width and depth of the channels) has a large impact on how evenly the reactant gases are spread across the active area of the membrane electrode assembly. Flow field design also affects water supply to the membrane and water removal from the cathode.

"There are more designs out there than you can imagine. No two fuel cell stack designs are the same. [Few] applications are really that close to each other in terms of power and intended area of use. We see a lot of variety."

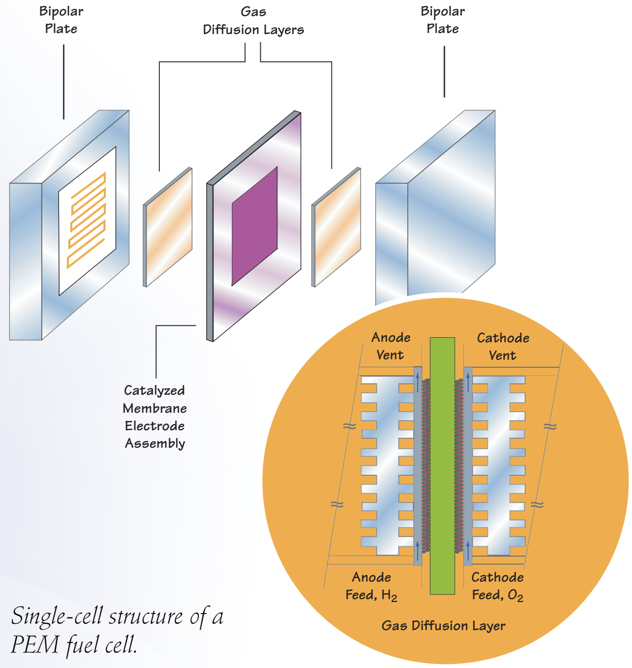
Stan Ream, automotive market leader at the Edison Welding Institute, "Fuel Cells: Fact, Not Fiction," Assembly Magazine, December 1, 2003



Photograph courtesy of General Motors.

Layers of fuel cell plate.

Each plate also acts as a current collector. Electrons produced by the oxidation of hydrogen must (1) be conducted through the anode, through the GDL, along the length of the stack, and through the plate before they can exit the cell; (2) travel through an external circuit; and (3) re-enter the cell at the cathode plate. With the addition of the flow fields and current collectors, the PEM fuel cell is complete; only a load-containing external circuit, such as an electric motor, is required for electric current to flow.



Single-cell structure of a PEM fuel cell.

Adapted from Gottesfeld, "The Polymer Electrolyte Fuel Cell: Materials Issues in a Hydrogen-Fueled Power Source," Los Alamos National Laboratory.

An animation of how fuel cells work is provided on DOE'S Hydrogen, Fuels Cells & Infrastructure Technologies Program web page (http://www.eere.energy.gov/hydrogenandfuelcells/education/fuel_cells.html).

DIFFERENT KINDS OF FUEL CELLS

Some types of fuel cells are better suited to transportation applications, while others are more appropriate for stationary and portable applications.

A usable power system requires anywhere from a few watts to hundreds of kilowatts. Higher-power applications may require the use of a fuel cell stack with hundreds of individual fuel cells. By stacking individual fuel cells together, it is possible to create more power, not unlike the effect of doubling, tripling, or quadrupling the number of batteries a device uses to increase the power available to operate that device. Many types of fuel cells can be made more efficient when they are used not only to generate electricity, but also to warm space and water with the heat they produce, a process known as cogeneration. In cogeneration, the power of the fuel cell is supplemented by its passive production of heat that can be used to heat air and water, thereby reducing energy consumption otherwise required to accomplish those tasks.

For example, in a building environment, a fuel cell producing electricity might also be heating water with its waste heat, a job that might otherwise require consumption of natural gas or electricity. Cogeneration can boost the overall efficiency for many types of fuel cells by 15–40%.

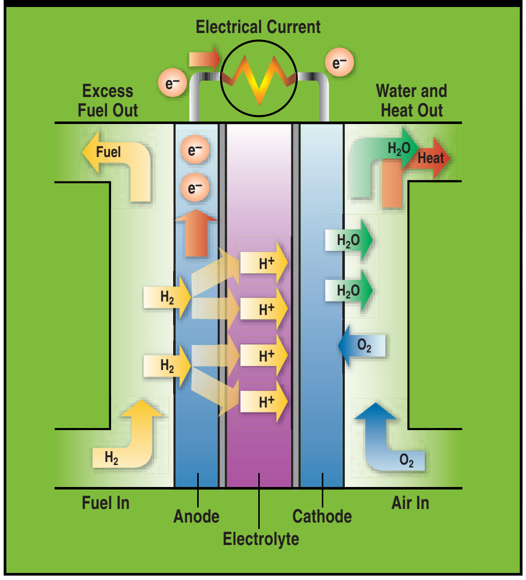
The following sections describe some of the better-developed fuel cell technologies. There are many more technologies in development, but most of them are too new or unproven to include in this publication.

Polymer Electrolyte Membrane Fuel Cell (PEMFC)

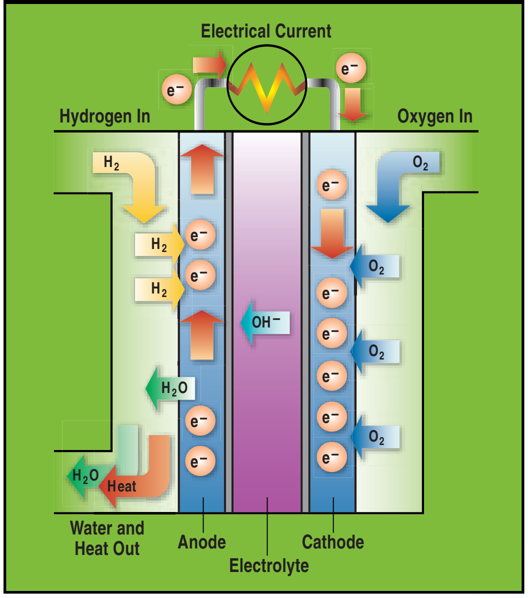
The electrical output of PEMFCs can vary rapidly when required, and they operate at a fairly low temperature (80°C/194°F), making them good candidates for use in light-duty vehicles and to replace rechargeable batteries in electronic devices. A PEMFC stack can generate from a few watts to 250 kW, making it very adaptable to a wide range of uses. A PEMFC system using direct hydrogen (as opposed to reforming other fuels; see discussion on page 18) can achieve efficiencies of 50–60% with cogeneration.

One type of PEMFC is the direct methanol fuel cell (DMFC), which uses methanol directly as its fuel, with no need for onboard conversion to hydrogen. Some of the features of direct methanol fuel cells include their low operating temperatures (50–100°C/122–212°F), their reliance on a readily available alternative fuel (methanol), and their clean operating characteristics. Because methanol is available today, direct methanol fuel cells could potentially be in use sooner than some other types of fuel cells, although widespread use would require a more developed methanol fuel infrastructure than currently exists.

Polymer Electrolyte Membrane Fuel Cell



Alkaline Fuel Cell



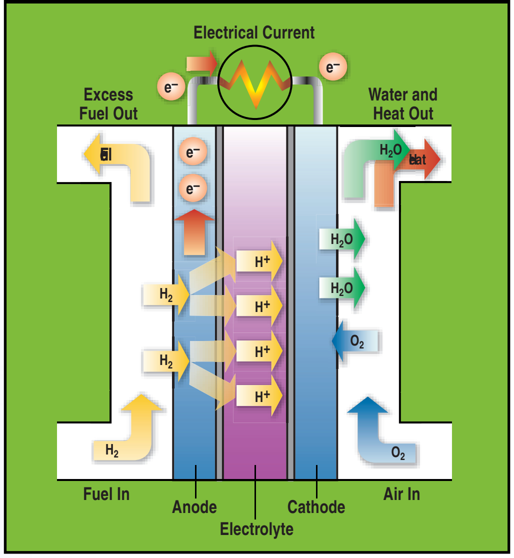
Alkaline Fuel Cell (AFC)

Another low-temperature (90–100°C/194–212°F) technology is the AFC. AFCs were first used by NASA in manned space flights, in large part because they offer higher performance than do many other types of fuel cells. They can achieve power-generating efficiencies of approximately 70% with per-cell output ranging from 300 W to 5 kW and are most likely to be used in space and transition applications. Electrocatalysts, such as nickel (Ni), silver (Ag), spinels, metal oxides, and noble metals, can be used in alkaline fuel cells. The primary disadvantage of AFCs is their high cost.

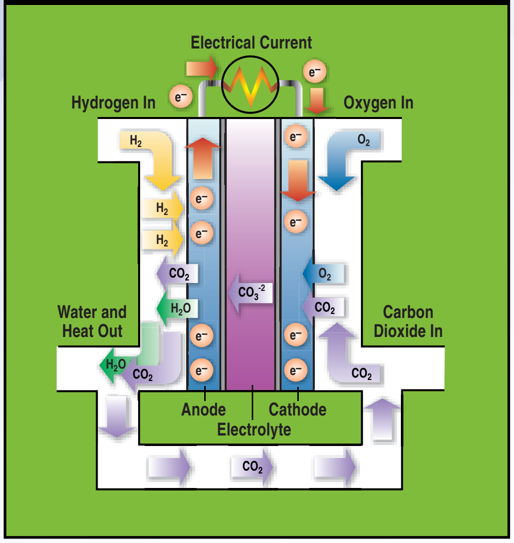
Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells have been used for years in buildings, hospitals, hotels, and electric utilities. As of 2004, over 200 PAFC units were installed around the world. They operate at higher temperatures (150–200°C/302–392°F) than do PEMFCs and AFCs. With cogeneration, their efficiency approaches 80%. They will most likely be used in stationary power generation environments. Existing PAFC systems can produce 200 kW to 1 megawatt (MW) of power.

Phosphoric Acid Fuel Cell



Molten Carbonate Fuel Cell



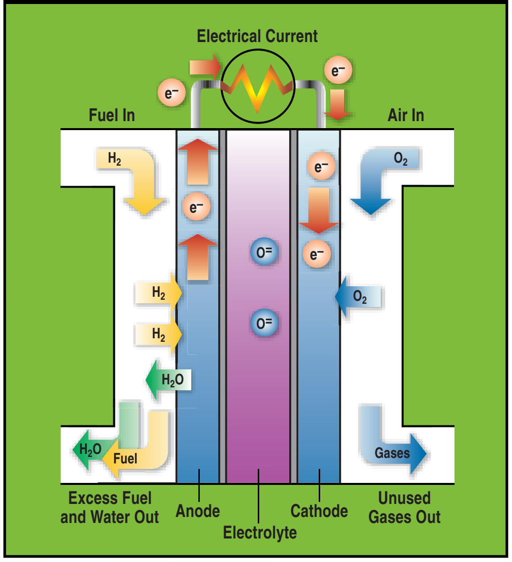
Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells are promising because they can extract hydrogen from a variety of unreformed fuels, rely on inexpensive catalysts, and offer high operating efficiency (nearly 60%, which increases to nearly 85% with cogeneration). These are high-temperature fuel cells (typically operating at 600–700°C/1,112–1,292°F), capable of producing 10 kW to 2 MW of power. They will most likely be used by electric utility companies and for distributed generation.

Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells incorporate a nonporous ceramic (metal oxide) electrolyte that requires them to operate at very high temperatures (650–1,000°C/1,202–1,832°F) — hot enough that fuel could be reformed within the fuel cell itself, eliminating the need for a separate fuel reformer. Without cogeneration, these fuel cells typically operate at 60% efficiency; with cogeneration, that number rises to approximately 85%. They can produce between 1 kW and 100 kW of power. Likely applications for SOFCs are in industrial and large central power-generating stations or as auxiliary power units for tractor-trailer trucks.

Solid Oxide Fuel Cell



COMPARISON OF FIVE FUEL CELL TECHNOLOGIES

Fuel Cell Type	Electrolyte	Power Output	Operating Temperature	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEMFC)	Solid organic polymer poly-perfluoro-sulfonic acid	5 W–250 kW	50–100°C 122–212°F	• Distributed generation • Portable power • Transportation	• Solid electrolyte reduces corrosion and management problems • Low temperature • Quick startup	• Low temperature requires expensive catalysts • High sensitivity to fuel impurities
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	350 W–5 kW	90–100°C 194–212°F	• Space • Transportation	• Cathode reaction faster in alkaline electrolyte, so high performance	• Expensive removal of CO_2 from fuel and air streams required
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	200 kW–1 MW	150–200°C 302–392°F	• Electric utility • Transportation	• Up to 85% efficiency in cogeneration of electricity and heat • Can use impure H_2 as fuel	• Requires platinum catalyst • Low current and power • Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	1 kW–100 kW	600–700°C 1112–1292°F	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Combined heat and power	• High temperature speeds corrosion and breakdown of cell components
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	10 kW–2 MW	500–1000°C 1202–1832°F	• Electric utility	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces corrosion and management problems • Combined heat and power	• High temperature speeds breakdown of cell components

FUELS AND INFRASTRUCTURE

Fuel cell systems can be powered by many types of fuel. Hydrogen is the first choice of many experts because when pure hydrogen is used to power fuel cells, no emissions (other than water and heat) are produced. Plus, hydrogen is almost completely nonpolluting when made from renewable resources. To enable the widespread use of hydrogen for fuel cells, however, we need a more extensive infrastructure to manufacture, transport, store, and sell hydrogen.

Photograph courtesy of DaimlerChrysler.

Hydrogen tanks for an urban fuel cell transit bus.

Where Does Hydrogen Come From?

Hydrogen is the most abundant element in the universe, but it is almost always found in combination with other substances — for instance, in water or fossil fuels. The hydrogen must be extracted from these substances. Depending on how hydrogen is produced, by-products (such as carbon oxides) may also be produced.

Hydrogen can be produced in several ways, including electrolysis of water, reforming of fossil fuels, and gasification of renewable resources.

Electrolysis

Electrolysis relies on the use of electricity to separate water into hydrogen and oxygen. Electricity can be generated by using renewable resources, such as wind, solar, hydro, and geothermal power, but most of the electricity used in the United States today is produced by coal-burning or nuclear power plants.

Reforming

Another way to produce hydrogen involves extracting it from fossil fuels. In this process, known as “reforming,” hydrogen-rich fuels (such as methanol, natural gas, or gasoline) pass through devices (reformers) that extract hydrogen from the fuel. One advantage of reforming is that it allows the use of conventional fuels and infrastructure. Drawbacks, however, include the release of CO_2 emissions as a by-product of the process. Scientists are researching ways to capture and sequester the carbon produced and prevent it from being released in the process.

Using Renewable Resources

Renewable resources, such as biomass (e.g., plant materials), are another potential source for hydrogen. As of 2004, no large-scale hydrogen production has been undertaken from renewables. DOE and the U.S. Department of Agriculture are funding research into using renewable resources as a source of hydrogen, but they probably won't be a significant source of hydrogen for decades.

Clearly, no single source for fuel or energy is ideal. A hydrogen economy will rely on multiple raw materials (feedstocks) and production methods to suit a wide range of resource, infrastructure, and use scenarios. It's this diversity and flexibility that makes hydrogen such a promising energy carrier.

How Do We Store, Transport, and Use Hydrogen?

One of the biggest challenges in making the transition to fuel cell power involves getting the hydrogen we need to where we need it. The United States lacks an adequate infrastructure for transporting, storing, and dispensing hydrogen in sufficient quantities. Hydrogen can be stored as a compressed gas, a liquid, or in a solid, but it is difficult to store in quantities large enough to generate the same amount of power as gasoline — it takes a lot of energy to compress and liquefy hydrogen. This issue is significant for fuel cell vehicles, which must have a driving range of 300–400 miles between refueling stops to compete with today's gasoline vehicles.

TECHNICAL CHALLENGES & BARRIERS TO COMMERCIALIZATION

Fuel Cell Cost and Durability

Some fuel cells are used today on a limited basis, although technical barriers to commercial-scale use remain. Cost and durability are the two biggest hurdles to commercializing fuel cells.

Manufacturing and materials costs for fuel cell stacks are high. For transportation fuel cell systems to succeed, their costs must compete with those of internal combustion engines, which are roughly $25–30 per kilowatt. For stationary systems, the cost will need to be approximately $400–750 per kilowatt. Although much progress has been made, the cost of today's fuel cell technology must be reduced by a factor of ten to meet cost targets.

To compete with other distributed power generation systems, stationary fuel cells must operate reliably for more than 40,000 hours. Fuel cells for transportation use must operate reliably for more than 5,000 hours. Today's fuel cell systems do not achieve those targets.

Hydrogen Production, Storage, and Delivery

As discussed above, there are many challenges associated with producing hydrogen, including cost, feedstock and resource issues, and generation of by-product emissions (such as CO_2). Current methods of transporting solid and liquid hydrogen also have drawbacks: they are expensive, provide insufficient energy density, and offer poor hydrogen release and regeneration. Safety, durability, and cost challenges remain for both on-and off-board storage of hydrogen.

Codes and Standards/ Public Acceptance

Codes and standards are needed to ensure the safe use of hydrogen, just as they do with the fuels commonly used today. While some codes and standards for hydrogen and fuel cell systems are already available, in many cases they do not fully address the new issues that arise when considering the needs of a future hydrogen economy. Government and industry partners are working with codes and standards organizations to identify and address the gaps, clarify and consolidate regulations, validate outdated test results, and ultimately develop new, more appropriate codes and standards that will ensure the safe use of hydrogen in the future

Another very real challenge to a hydrogen economy is public acceptance of hydrogen as an everyday fuel. Misinformation about the safe use of hydrogen can lead to fear and resistance to hydrogen demonstration projects in local communities, which in turn jeopardize long-term commercialization efforts. In addition, although interest in fuel cell technology is increasing, many people do not yet view fuel cells as a viable alternative.

Experience greatly enhances understanding of and comfort with any new technology. Education will help communicate the facts about hydrogen safety, and over time, as research advances, hydrogen and fuel cell demonstration projects will help to raise the public's awareness of the promise and challenges of fuel cells and a hydrogen economy.

"Ultimately, hydrogen and electricity, our two major energy carriers, will come from sustainable energy sources, although fossil fuel will likely remain a significant and transitional resource for many decades."

International Energy Agency Hydrogen Program http://www.ieahia.org

DEMONSTRATIONS

Photograph courtesy of DaimlerChrysler.

Fuel cell demonstration bus.

Fuel cell demonstrations are currently under way in the United States, Canada, Europe, and Japan, typically as partnerships between government and industry. The goal of all these projects is to validate fuel cell and hydrogen technology in real-world environments. For more information on technology validation projects, go to *http://www.eere.energy.gov/hydrogenandfuelcells.*

IN SUMMARY

Improving our country's energy situation is a challenge, and the stakes are high. To achieve a hydrogen economy, we must lower the cost of fuel cells and hydrogen, devise new methods for storing sufficient amounts of hydrogen on vehicles to support reasonable driving ranges, and solve delivery and refueling infrastructure dilemmas.

Much of our nation's best scientific and technical talent — in the national laboratories, academia, and industry — is working to address these concerns. Demonstration projects under way today are showing that hydrogen-powered fuel cells are capable of changing the way we power our vehicles, buildings, and portable devices.

Together, with public and private support, we can take these technologies from the research lab to demonstration to commercialization and widespread use, realizing a cleaner, self-sufficient, and sustainable energy futur

"Those who say our plan is difficult are stating the obvious. It is a huge challenge with many obstacles to overcome. But we believe hydrogen is the key to a cleaner, safer, and healthier energy future, and we are confident we can succeed. The automakers and the energy companies agree. The question we face today is how fast this effort should proceed. Some observers say "stay the course" and stick with the internal combustion engine. They propose more government mandates to improve automobile fuel efficiency and higher gas taxes to discourage consumption.

If we follow their advice, in 30 years we will still be debating ways to reduce auto emissions and our dependency on foreign oil. But if we follow President Bush's bold lead, young adults in 2030 will be chuckling about ancient history, the days when their elders worried about imported oil, polluting emissions, and energy security. That is a vision worth achieving."

U.S. Secretary of Energy Spencer Abraham, April 14, 2003

GLOSSARY

Alkaline Fuel Cell (AFC)
A type of hydrogen/oxygen fuel cell in which the electrolyte is concentrated potassium hydroxide (KOH), and hydroxide ions (OH^-) are transported from the cathode to the anode.

Anode
The electrode at which oxidation (a loss of electrons) takes place. For fuel cells, the anode is electrically negative; for the opposite reaction of electrolysis, the anode is electrically positive.

Bipolar Plate
Plate in a fuel cell stack that acts as an anode for one cell and a cathode for the adjacent cell. The plate, made of graphite, metal, or a conductive polymer, usually incorporates flow channels for the fluid feeds and may also contain conduits for heat transfer.

Carbon (C)
An atom and primary constituent of hydrocarbon fuels. Carbon is routinely left as a black deposit on engine parts, such as pistons, rings, and valves, by the combustion of fuel.

Carbon Dioxide (CO_2)
A colorless, odorless, noncombustible gas that is slightly more than 1.5 times as dense as air and becomes a solid (dry ice) below –78.5°C. It is present in the atmosphere as a result of the decay of organic material and the respiration of living organisms. It is produced by the burning of wood, coal, coke, oil, natural gas, or other fuels containing carbon.

Carbon Monoxide (CO)
A pollutant from engine exhaust that is a colorless, odorless, tasteless, poisonous gas that results from incomplete combustion of carbon with oxygen.

Catalyst
A chemical substance that increases the rate of a reaction without being consumed; after the reaction, it can be recovered from the reaction mixture chemically unchanged. The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature.

Catalyst Poisoning
The process of impurities binding to a fuel cell's catalyst, lowering the catalyst's ability to facilitate the desired chemical reaction. See also Fuel Cell Poisoning.

Cathode
The electrode at which reduction (a gain of electrons) occurs. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the protons and oxygen to form water.

Cogeneration
The production of electricity or heat from usable waste heat generated by another process (such as fuel cell operation).

Composite
Material created by combining materials differing in composition or form to obtain specific characteristics and properties. The constituents retain their identity; they can be physically identified, and they exhibit an interface between one another.

Compressed Natural Gas (CNG)
Mixtures of hydrocarbon gases and vapors, consisting principally of methane in gaseous form that has been compressed for use as a vehicular fuel.

Current Collector
Term used to describe the conductive separator plate in a fuel cell that collects electrons (on the anode side) or disburses electrons (on the cathode side). Current collectors are microporous (to allow for fluid flow through them) and lie in between the catalyst/ electrolyte surfaces and the bipolar plates.

Density
Density is defined as the amount of mass in a unit volume. Density varies with temperature and pressure.

Direct Methanol Fuel (DMFC)
A type of fuel cell in which the fuel is methanol (CH3OH) that is oxidized directly at the anode instead of first being reformed to produce hydrogen. The electrolyte is typically a PEM.

Electrode
A conductor through which electrons enter or leave an electrolyte. Batteries and fuel cells have a negative electrode (the anode) and a positive electrode (the cathode).

Electrolysis
A process that uses electricity to cause a reaction that breaks chemical bonds.

Electrolyte
A substance that conducts charged ions from one electrode to the other inside a fuel cell.

Electron
A stable atomic particle that has a negative charge; the flow of electrons through a substance constitutes electricity.

Energy
The quantity of work a system or substance is capable of doing, usually measured in British thermal units (Btu) or Joules (J).

GLOSSARY

Energy Density
Amount of potential energy in a given volume of fuel.

Ethanol (CH_3CH_2OH)
An alcohol composed of carbon, hydrogen, and oxygen. It is a clear, colorless liquid and is the same alcohol found in beer, wine, and whiskey. Ethanol is produced by fermenting a sugar solution with yeast.

Exhaust Emissions
Pollutants emitted into the atmosphere through any opening downstream of the exhaust ports of an engine.

Exothermic
A chemical reaction that gives off heat.

Feedstock
Raw material supplied for production of electricity, gases, or chemicals.

Fuel
A material used to create heat or power through chemical conversion in such processes as burning or electrochemistry.

Fuel Cell
A device that uses hydrogen and oxygen to create electricity through an electrochemical process.

Fuel Cell Poisoning
The lowering of a fuel cell's efficiency due to impurities in the fuel or air binding to the catalyst.

Fuel Cell Stack
Individual fuel cells connected in series. Fuel cells are stacked to increase voltage.

Fuel Processor
Device used to generate hydrogen from fuels, such as natural gas, propane, gasoline, methanol, and ethanol, for use in fuel cells.

Gas Phase of Matter
Fuel gas, such as natural gas, undiluted liquefied petroleum gases (vapor phase only), liquefied petroleum gas-air mixtures, or mixtures of these gases.

Gas Diffusion
The movement of gas phase molecules from a region of high concentration to a region of low concentration. Gases diffuse very quickly and liquids diffuse much more slowly; solids diffuse at very slow (but often measurable) rates. Molecular collisions make diffusion slower in gases, liquids, and solids.

Graphite
Mineral consisting of a form of carbon that is soft, black, and lustrous and has a greasy feeling; used in pencils, crucibles, lubricants, paints, polishes, reactors, and electrodes.

Greenhouse Effect
Warming of the Earth's atmosphere due to gases in the air that allow solar radiation (visible, ultraviolet) to reach the Earth's atmosphere but do not allow the emitted infrared radiation to pass back out the Earth's atmosphere.

Greenhouse Gas (GHG)
Gases in the Earth's atmosphere that contribute to the greenhouse effect: carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), and chlorofluorocarbons (CFCs).

Hydrocarbon (HC)
An organic compound containing only carbon and hydrogen, usually derived from fossil fuels, such as petroleum, natural gas, and coal; an agent in the formation of photochemical smog.

Hydrogen (H_2)
The simplest and lightest element in the universe, which exists as a gas except at low temperatures. Hydrogen gas is colorless, odorless, and flammable when mixed with oxygen over a wide range of concentrations. Hydrogen forms water when combusted or when otherwise reacted with oxygen, as in a fuel cell.

Hydrogen-Rich Fuel
A fuel that contains a significant amount of hydrogen, such as gasoline, diesel fuel, methanol (CH_3OH), ethanol (CH_3CH_2OH), natural gas, and coal.

Impurities
Undesirable foreign material(s) in a pure substance or mixture.

Internal Combustion Engine (ICE)
An engine that converts the energy contained in a fuel inside the engine into motion. Combustion engines use the pressure created by the expansion of gases to do mechanical work.

Ion
Atom or molecule that carries a positive or negative charge because of the loss or gain of electrons.

Kilowatt (kW)
A unit of power equal to about 1.34 horsepower, or 1,000 watts.

Liquefied Hydrogen (LH_2)
Hydrogen in liquid form. Hydrogen can exist in a liquid state, but only at extremely cold temperatures. Liquid hydrogen typically has to be stored at -253°C (-423°F).

GLOSSARY

The temperature requirements for liquid hydrogen storage necessitate expending energy to compress and chill the hydrogen into its liquid state.

Liquefied Petroleum Gas (LPG)
Any material that consists predominantly of any of the following hydrocarbons or mixtures of hydrocarbons: propane, propylene, normal butane, isobutylene, and butylenes.

Megawatt (MW)
A unit of power equal to one million watts.

Membrane
The separating layer in a fuel cell that acts as an electrolyte and as a barrier film separating the gases in the anode and cathode compartments of the fuel cell.

Methane (CH_4)
See natural gas.

Methanol (CH_3OH)
Methanol is the simplest of the alcohols. It has been used, together with some of the higher alcohols, as a high-octane gasoline component and is a useful automotive fuel in its own right.

Milliwatt (mW)
A unit of power equal to one-thousandth of a watt.

Molten Carbonate Fuel Cell (MCFC)
A type of fuel cell that contains a molten electrolyte. Operating temperatures are typically near 650°C.

Nafion®
Perfluorosulfonic acid in a solid form that is usually the electrolyte used in PEM fuel cells.

Natural Gas
A naturally occurring gaseous mixture of simple hydrocarbon components (primarily methane) used as a fuel.

Nitrogen (N_2)
A colorless, tasteless, odorless gas that constitutes 78% of the atmosphere by volume.

Nitrogen Oxides (NO_x)
Any chemical compound of nitrogen and oxygen. Nitrogen oxides result from high temperature and pressure in the combustion chambers of automobile engines and other power plants during the combustion process. When combined with hydrocarbons in the presence of sunlight, nitrogen oxides form smog. A basic air pollutant; automotive exhaust emission levels of nitrogen oxides are regulated by law.

Noble Metal
A metallic element that resists oxidation or corrosion, such as platinum, gold, ruthenium, silver, rhodium, rhenium, osmium, iridium, and palladium.

Oxidation
Loss of one or more electrons by an atom, molecule, or ion.

Oxygen (O_2)
A colorless, tasteless, odorless, gaseous element that makes up about 21% of air.

Permeability
Ability of a membrane or other material to permit a substance to pass through it.

Phosphoric Acid Fuel Cell (PAFC)
A type of fuel cell in which the electrolyte consists of concentrated phosphoric acid (H_3PO_4) and protons (H^+) transported from the anode to the cathode. The operating temperature range is generally 160–220°C.

Polymer
Natural or synthetic compound composed of repeated links of simple molecules.

Polymer Electrolyte Membrane (PEM)
A solid membrane, similar in consistency to thick plastic wrap, used as an electrolyte in fuel cells. The membrane allows protons to pass through it, but blocks electrons.

Proton
Atomic particle in the nucleus of an atom that carries a positive electric charge.

Reactant
A chemical substance present at the start of a chemical reaction.

Reactor
Device or process vessel in which chemical reactions take place.

Reformer
Device used to generate or produce the hydrogen from fuels, such as natural gas, propane, gasoline, methanol, and ethanol, for use in fuel cells.

Reforming
A chemical process in which hydrogen-containing fuels react with steam, oxygen, or both to produce a hydrogen-rich gas stream.

GLOSSARY

Reformulated Gasoline
Gasoline that is blended so that, on average, it reduces volatile organic compounds and air toxics emissions relative to conventional gasolines.

Renewable Energy
A form of energy that is never exhausted because it is renewed by nature (within short time scales; e.g., wind, solar radiation, hydro power).

Solid Oxide Fuel Cell (SOFC)
A type of fuel cell in which the electrolyte is a solid, nonporous metal oxide, typically zirconium oxide (ZrO_2) treated with Y_2O_3, and O_2^- is transported from the cathode to the anode. Any CO in the reformate gas is oxidized to CO_2 at the anode. Temperatures of operation are typically 800–1,000°C.

Steam Reforming
The process for reacting a hydrocarbon fuel, such as natural gas, with steam to produce hydrogen as a product. This is a common method of bulk hydrogen generation.

Watt (W)
A unit of power equal to one joule of energy performed per second; 746 watts are the equivalent of one horsepower. The watt is named for James Watt, Scottish engineer (1736–1819) and pioneer in steam engine design.

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A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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